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THOUGHTS ON PROGRESS IN ROTATING-WING AERODYNAMICS

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INTRODUCTION

As a framework for discussing where we are and what needs doing about aerodynamics of helicopter-type rotors, it is convenient to think in terms of current problems as seen by the user, and that approach is used in this paper. One well-recognized problem is the need for increased maneuver capability at cruise speed; this one leads into several sticky aspects of basic rotor aerodynamics. A second is cruise efficiency; in conjunction with maneuver capability, this problem leads into the question of aerodynamic redesign of rotors. A third problem, or actually a convenient grouping of problems, is noise, blade stress, and vibration; this grouping was chosen to lead into discussion of what might be done to reduce the unwanted effects of blade-tip vortices. Following discussion of these problems, a few tentative thoughts on getting faster progress virtually without added cost are given.

MANEUVER CAPABILITY AT CRUISE SPEEDS

Aerodynamic Anomalies

High accelerations at cruise speeds, by requiring high thrust when the retreating blade is already at a high angle of attack, leads straight to the question of retreating-blade section characteristics and boundary-layer

behavior at high angles of attack. Here we are faced with a number of anomalies. For example, studies of reference 1 as well as several subsequent studies have indicated predominantly forward flow on the blade surface after high-angle flow separation, while other studies such as that of reference 2 have shown predominantly spanwise, outward flow. As another example, unpublished results of tuft studies on an autogiro rotor (for conditions generally similar to those reported on in reference 3) have shown both types of flow, with the outward flow occurring subsequent to the forward flow during each revolution. Thus we have anomalies in that the separated flow is sometimes two dimensional and other times three dimensional. For the first case the readily available two-dimensional airfoil characteristics can be expected to be usable; for the second case they cannot, and differences could be large as well as relatively unknown. Along the same lines, the pressure-distribution studies reported in references 4 and 5 show normal two-dimensional chordwise distribution-plot shapes (see the upper portion of figure 1) for normal-force coefficients (C_N 's) up to and even above the maximum C_N obtained in static two-dimensional tests. Shapes such as that shown in the lower portion of figure 1 are found in references 4 and 5 for still higher C_N 's, for example, 1.7. The $C_N = 1.7$ plot represents at least a local lift bonus over the static two-dimensional case but also represents a pitching-moment change which may tend to discourage operation at this condition in spite of any net increase in lift capability. Reference 6 shows that for a hovering, unstalled blade the boundary-layer flow is surprisingly two dimensional. Reference 7, on the other hand, shows evidence of lift-curve extension on a propeller. This problem of at least part-time deviations from the conveniently available

two-dimensional data, then, seems largely confined to angles of attack above the simple-flow-condition stall angle.

In the case of swept wings for airplanes, it has surely paid off to understand the difference in maximum-lift flow mechanism as contrasted to that for straight wings. Similarly, an understanding of the corresponding flow mechanism for the rotor blade should pay off. One possible experimental ingredient for better understanding - testing of several full-scale rotors - will be discussed in a later section.

Jet-Flap Rotor

Thus far, the question of what lift can be obtained from a conventional blade has been considered. It is interesting to note that at least one high-lift device has shown promise of working in a rotor. Specifically, reference 8 reports successful wind-tunnel operation of a full-scale rotor at a tip-speed ratio of 0.5 and a blade mean lift coefficient \bar{c}_l (computed as $6C_T/\sigma$) of about one. Ordinarily, retreating-blade stall effects stop such tests far short of this combination.

Blade-Motion Problems in Maneuvers

Another aspect of maneuver capability is blade-motion stability, blade-motion amplitude, and blade-motion vibration content. Some recent analytical studies in this connection are reported in reference 9. In that paper, the importance of the "aerodynamic spring" action on the forward blade is explained. It is shown that, for nonlinear calculations, both the blade stability and transient response are drastically affected by the blade azimuth angle at which a gust (or control) disturbance is introduced. It is also shown

that blades lacking a high margin of stability will, as compared to highly damped blades, be more prone to go out of track and cause vibration when disturbed. These studies are illustrative of analytical treatments which can profitably be extended to include more and more degrees of freedom, provided that validity can be established for the successive ingredients. Such work should help increase the usable steady value of normal acceleration, which tends, at cruise speeds, to be limited by vibration and blade behavior.

Remote-Controlled Flight-Test Articles

As a final point concerning the maneuver problem, it seems necessary that both in extending the aerodynamic maximum, and in trying to close the large gap between practical operating limits and this aerodynamic maximum, flight tests must be a part of the picture. Because of the general violence and the nonlinearities and uncertainties involved, it is suggested that the use of pilotless, instrumented, remote-controlled drone helicopters is worth serious consideration for the most advanced testing, both for research and development purposes.

CRUISE EFFICIENCY

Progress is being made in reducing helicopter fuselage drag; also, blade tip speeds have risen. These factors make blade-section profile losses stand out as a major source of cruise power loss, and lead to reconsideration of laminar-flow airfoil sections.

Laminar-Flow Sections

Blade construction methods have improved immensely since the period when laminar-flow sections were previously tried and considered impractical. Current construction methods, with some care and adaptation, may provide sufficient contour accuracy for holding laminar flow. Extra processing for accuracy could, if desired, be restricted to the outer part of the blade since this high-speed portion accounts for most of the skin-friction type loss. Incidentally, difficulties in holding laminar flow on airplanes do not provide an adequate precedent because the typical airplane-wing Reynolds number is so much higher than that for a rotor blade.

Before re-embarking on laminar-flow-airfoil efforts, however, it appears extremely important to determine with actual rotor blades the effect on the ability to hold laminar flow of a variety of practical operating problems such as accumulation of bug spatters, salt, and dirt. Such checks should include the outer portion of current wide-chord, main-rotor blades, since high Reynolds number makes the problem harder. The photographic transition-check method described in reference 6 would seem well suited.

ALL-AROUND BLADE AERODYNAMIC REDESIGN

Since maneuver capability as well as cruise efficiency call for blade redesign, a broader look than just given seems in order. In fact, there are so many indications of intent to work toward "optimum" blade designs, with radial variations in thickness, camber, chord, and the like, and of intent to work with inboard-download problems as well as outboard

profile losses, that the question seems to be how, rather than whether, such effort should take place.

Tip Stall Versus Inboard Stall

First of all, perhaps a reminder is in order that when helicopter blades with no twist were used they really did stall first and most seriously in the region of the blade tips. Figure 2, taken from reference 1, illustrates this point.⁽¹⁾ On the other hand with -8° twist, even the elementary uniform-inflow theory typically predicts stall earlier at the $3/4$ radius than at the tip, making it reasonable to entertain the use of thinner, less cambered, smaller nose-radius sections toward the tip.

Tolerable Camber

Second, since a blade with no camber anywhere will be far from optimum aerodynamically, it seems imperative that the issue of judicious use of camber, versus no camber anywhere, be resolved. At one extreme, hopes for the practical success of the jet flap as actually tested in reference 8 hinge on the ability to tolerate really large blade-section pitching moments. At the other extreme, there are still reports of serious vibration being caused by extremely small camber values, even with uniformly built sets of blades. Then again, the really obvious excesses of camber through history have involved amounts so large as to twist off part of a blade or to cause narrow

(1) Note: Because no tufts were mounted at the extreme tip and there is reason to believe the flow on the outer few percent may remain unseparated, the outer rim of the shading shown in the original plot of reference 1 is removed in figure 2.

escapes from outside loops. Carefully conducted measurements of effect of small camber increments on vibration for several established helicopter types would seem a prerequisite to selection of airfoils for improved rotors.

Systematic Series of Full-Scale Blades

Third, it is believed that the accurate construction and careful flight testing of at least a modest-sized series of full-scale blades with systematically varied parameters is now warranted. One reason for such a step is that anomalies such as those mentioned in the "maneuver capability" section cast too much doubt on theoretical and small-scale-model work. Such full-scale information should provide clues and anchor points which would greatly aid the other types of effort planned toward resolving these anomalies and doubts. Perhaps such rotors should be built in groups of two or three, with six months to a year between groups to allow as much of the progress as possible to be made by way of more varied, interrelated small-scale and theoretical work. In view of the large production rates for helicopters, the cost might be warranted as a part of developmental product-refinement work.

Conditions for Adequacy of Current Theory

Before leaving the subject of blade design it is desired to emphasize that the anomalies referred to relate to cases where sizable areas involve blade-section conditions inviting flow separation. When, instead, all regions other than those for very low dynamic pressures involve low or moderate angles of attack, analyses based on simple two-dimensional characteristics normally seem to be quite appropriate and adequate.

NOISE, BLADE STRESS, AND VIBRATION

These well-known problems have one aspect in common, and that is the only aspect to be discussed here. Specifically, the striking of tip vortices left by preceding blades is widely believed to contribute to all of these problems. Considerable proof to this effect has been accumulated and need not be reviewed here.

Since this vortex is such a nuisance, it seems reasonable to illustrate a few preliminary ideas on ways to shift it partly out of the way as well as to weaken it. Blowing a sheet of air from the end of a lifting surface (fig. 3, part 1) will, per reference 10, move the tip vortex outward. It is also shown in reference 10 that blowing at a downward angle can hold the vortex down and, to judge from the flow photographs, weaken or spread it - all beneficial for the purpose at hand. Blowing straight out in plan view is unthinkably wasteful; if done from a swept tip as in part 2 of figure 3, however, about 85 percent of the jet energy would be used to turn the rotor, and the scheme can be looked upon as a modification to a tip-jet-driven rotor. Tip sweep may have an additive effect in reducing noise, as well as serving to delay Mach number problems of all types, but introduces structural problems; also, the position of the jet sheet in relation to the solid surface may be important. Alternate arrangements are therefore illustrated in parts 3, 4, and 5 of figure 3. No data have been found to show whether or not the sweptback sheet of air would retain its vortex-control effectiveness. If it does, and if the increased effective blade radius (caused by shifting the vortex out) should roughly offset the 15 percent loss, then on a tip-driven

design reductions in noise and vibration should be obtainable essentially "for free."

As a more prosaic aspect of the tip-vortex noise and vibration problem, the effects on it of changes in planform and twist should be one of the factors assessed during the previously discussed systematic variation of blade aerodynamic design.

WAYS TO LEARN MORE FROM WHAT IS BEING DONE

In the midst of machine computations and quantities of data, the simpler ways of learning things, and of keeping track of where we stand, or of making quick comparisons with past experience, tend to get lost. The simpler techniques can still be of value, and a few examples follow.

Rules of Thumb and Indexes

In reference 11, a rule of thumb for estimating available all-out, demonstration-type-maneuver normal acceleration was suggested; that is, to take the ratio of section $c_{l_{max}}$ to level-flight blade mean lift coefficient \bar{c}_l . Where the needed data have been obtainable, this crude approach has come surprisingly close. One inference is that since there have to be some areas operating materially below $c_{l_{max}}$, some local c_l values above the simply determined $c_{l_{max}}$ are being realized.

The struggle with the blade-stall anomalies mentioned earlier makes it important to know how consistently this happens. As an even simpler approach than comparing with the complete rule of thumb, perhaps the initial reporting of well-instrumented severe maneuvers could include the value of

\bar{c}_1 corresponding to maximum acceleration. This step should be very easy for the original investigator, though it seems usually to become impossible for someone else at a later date. This number should, incidentally, be of great interest to those conducting such flights, as well as to the specialist in rotor aerodynamics.

A modern criterion for estimating practical operating limits (such as may be imposed by blade stall, for example) is given in reference 12, based in essence on rate of power rise with change in flight condition. The tables of reference 13 provide supplementary numbers which indicate, from power considerations, the severity of conditions between or beyond the criterion values. With experience this approach may give a good measure for conditions beyond the criteria boundaries, of severity from considerations of overall behavior including vibration and controllability. It would appear that a gap will remain, however, at least in respect to the margin of safety between a mild condition and a limiting condition; that is, where the power changes are relatively insensitive to operating conditions. To fill this gap, an index similar to the long-familiar simply estimated tip and inboard retreating-blade angles of attack is still needed. Perhaps the statement of \bar{c}_1 , tip-speed ratio μ , and tip-path-plane angle of attack would help - or perhaps the simply estimated angles of attack just mentioned, if both were given together with μ , would still serve.

Comparison With One Theory

As more experimental results on rotor aerodynamics become available, their cross-comparison will be aided if each is compared to the same rotor theory. To aid this process, NASA has recently published references 12

and 13, providing easily used though basically complex theory. Comparison with this easily used theory need not be viewed as taking the place of any hand-tailored calculations deemed desirable, but rather as a supplementary step to aid data interpretation and, in conjunction with similar comparisons for other tests, to help judge needed additions to or modifications in current theory.

Pooling of Computer Processes

Studies such as that of reference 9 (blade dynamic behavior) can profit from extensions to include more and more coupled degrees of freedom in the rotor dynamics treatment. Numerous organizations have, and will continue to, set up computing-machine processes for adding coupled degrees of freedom. Perhaps a serious effort should be made to find ways to pool or otherwise make multiple use of established computing-machine programs or results, especially when these programs or results are either mechanical tools separable from creative thinking, or else represent a clear-cut stage of refinement.

CONCLUDING REMARKS

Anomalies in rotor aerodynamics have been pointed out, the resolution of which would help solve recognized problems. It appears that the inevitable efforts to develop "optimum" rotor blades might be guided in such a way as to help resolve these anomalies. Several steps which should in any case precede major effort towards aerodynamically improved rotors have been suggested. Finally, as means toward more efficient progress, it has been suggested that the practice of using simple rules of thumb be continued, that

outwardly unrelated test results be cross-compared through one theory, and that serious thought be given to means for pooling complex computing-machine programs for basic ingredients in rotor aeroelastic treatments.

REFERENCES

1. Gustafson, F. B.; and Myers, G. C., Jr.: Stalling of Helicopter Blades.
NACA Rept. 840, 1946.
2. Sweet, George E.; Jenkins, Julian L., Jr.; and Winston, Matthew M.:
Results of Wind Tunnel Measurements on a Lifting Rotor at High Thrust
Coefficients and High-Tip Speed Ratios. NASA TN D-2462, 1964.
3. Bailey, F. J., Jr.; and Gustafson, F. B.: Observations in Flight of the
Region of Stalled Flow Over the Blades of an Autogiro Rotor. NACA
TN 741, 1939.
4. Scheiman, James; and Kelley, Henry L.: Comparison of Flight Measured
Helicopter Rotor Blade Chordwise Pressure Distributions and Two Dimen-
sional Airfoil Characteristics. Proceedings of CAL-TRECOM Symposium on
Dynamic Loads Problems Associated with Helicopters and V/STOL Aircraft,
Buffalo, New York, June 1963, The U.S. Army Transportation Research
Command, Fort Eustis, Virginia/Cornell Aeronautical Research Lab., Inc.,
Buffalo, New York, Volume I.
5. Scheiman, James: A Tabulation of Helicopter Rotor-Blade Differential
Pressures, Stresses, and Motions as Measured in Flight. NASA TM X-952,
1964.
6. Tanner, W. H.; and Yaggy, P. F.: Experimental Boundary Layer Study on
Hovering Rotors. Proceedings of the Twenty-Second Annual National
Forum of the American Helicopter Society, May 1966.
7. Yaggy, P. F.; and Rogallo, V.: A Wind Tunnel Investigation of Stall Flut-
ter Characteristics of a Supersonic Type Propeller at Positive and
Negative Thrust. NASA MEMO 3-5-59A, 1959.

8. McCloud, John L., III; Evans, William T.; and Biggers, James C.: Performance Characteristics of a Jet-Flap Rotor. Proceedings of the Conference on V/STOL and STOL Aircraft, Ames Research Center, Moffett Field, California, April 4-5, 1966. NASA SP-116.
9. Jenkins, Julian L., Jr.: Calculated Blade Response at High Tip-Speed Ratios. Proceedings of the Conference on V/STOL and STOL Aircraft, Ames Research Center, Moffett Field, California, April 4-5, 1966. NASA SP-116.
10. Smith, V. J.; and Simpson, C. J.: A Preliminary Investigation of the Effect of a Thin High Velocity Tip Jet on a Low Aspect Ratio Wing. Australian Aerodynamics Note 163. June 1957.
11. Gustafson, F. B.; and Crim, Almer D.: Flight Measurements and Analysis of Helicopter Normal Load Factors in Maneuvers. NACA TN 2990, 1963.
12. Tanner, W. H.: Charts for Estimating Rotary Wing Performance in Hover and at High Forward Speeds. Nov. 1964. NASA-CR-114.
13. Tanner, W. H.: Tables for Estimating Rotary Wing Performance at High Forward Speeds. Nov. 1964. NASA-CR-115.

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Figure 3.- Tip-blowing arrangements for altering blade-tip vortices.

DIFFERENTIAL
PRESSURE

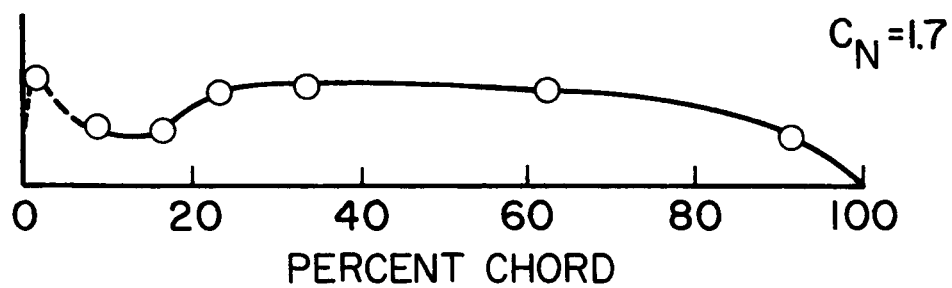
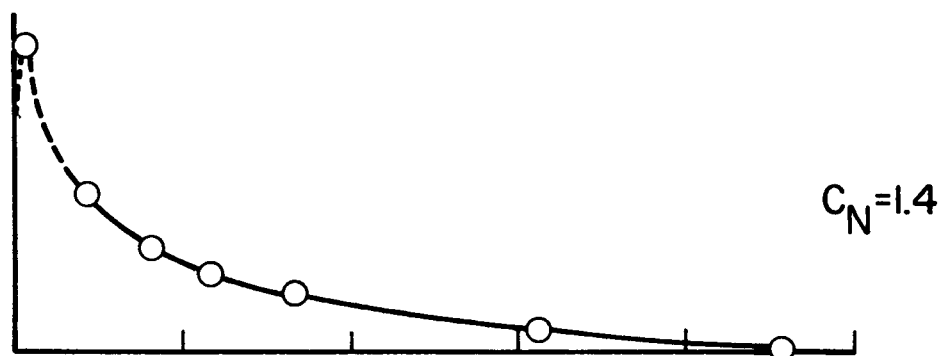


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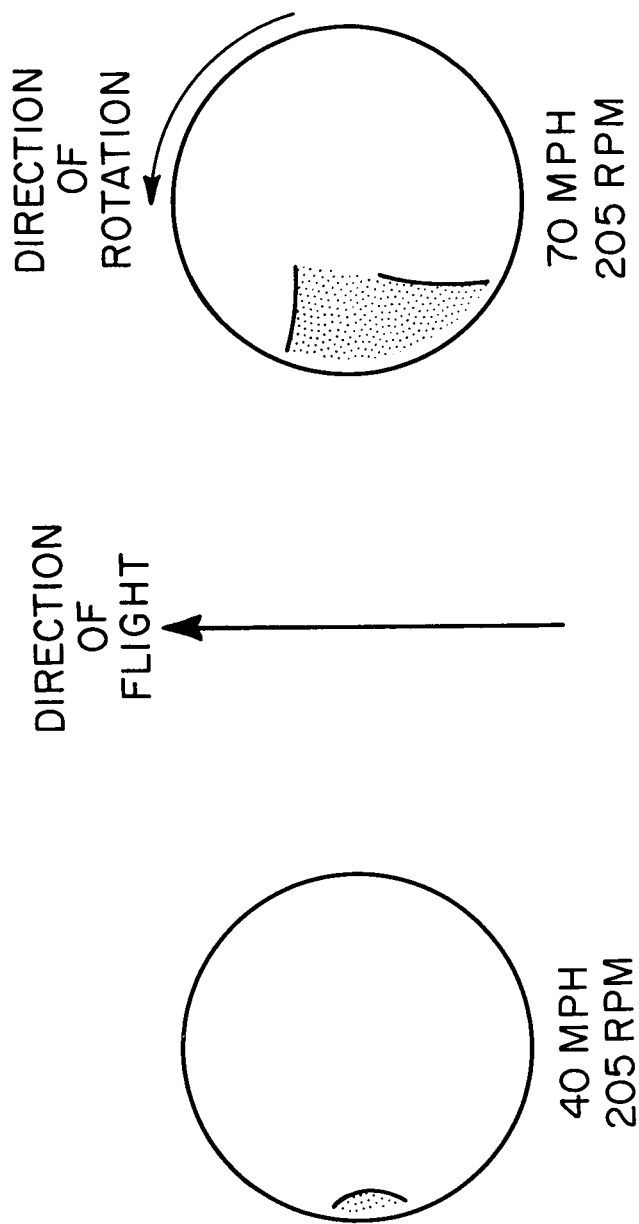


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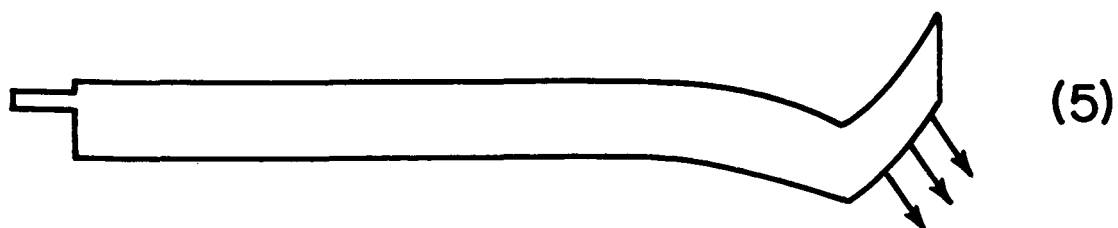
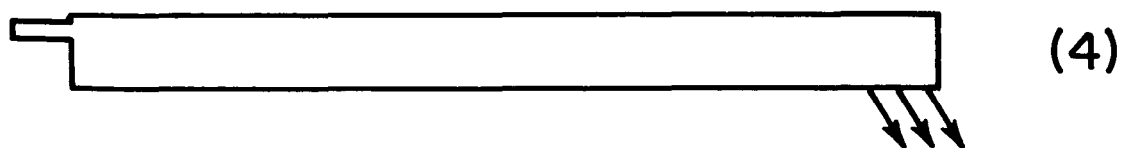
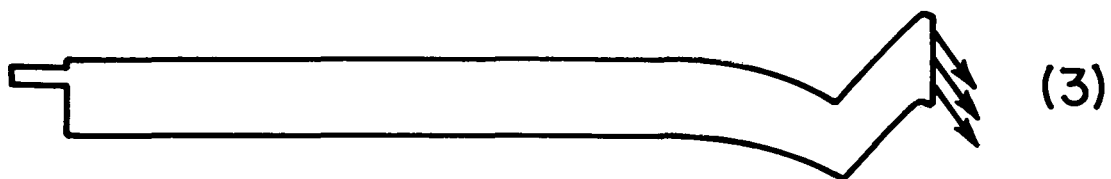
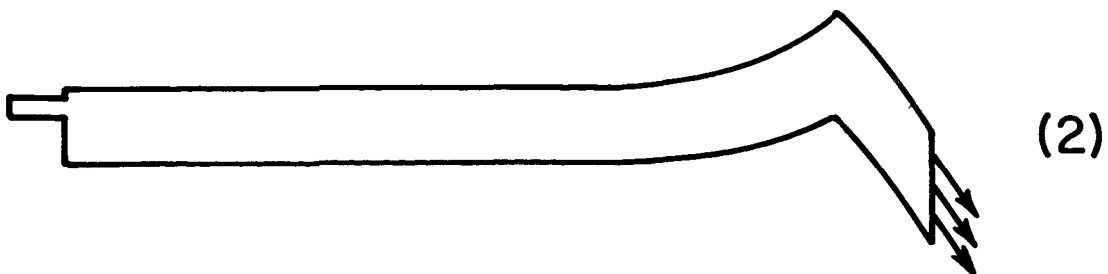
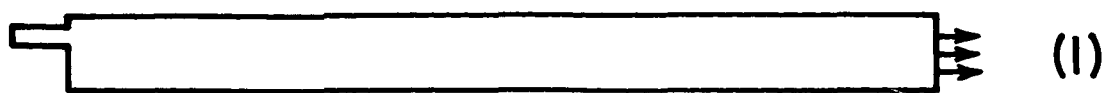


Figure 3.- Plan view of tip-blowing arrangements for altering blade-tip vortices.